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Experimental Study on the Utilisation of Independent Wire Fibre Core Steel Wire Rope Braces to Enhance the Stability of a 2d Concrete Portal against Lateral Forces

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Abstract

Structural stability in construction, especially in buildings exposed to lateral forces due to earthquakes, is very important to consider. This research aims to explore the effectiveness of using Independent Wire Fibre Core (IWFC) steel wire rope braces in strengthening two-dimensional (2D) concrete portals. The method used is a series of laboratory tests to measure the performance of concrete portals equipped with IWFC braces. Concrete portals with dimensions of 1.00 m in the width direction and 1.50 m in the height direction were tested with lateral loading to simulate the effects of earthquakes. The test results showed that the use of IWFC braces increased the load resistance capacity of the portal by 16.13%, from 14.00 kN to 26.13 kN, and reduced the deviation by 30.43%, from 2.30 mm to 1.68 mm. In addition, the analysis showed an increase in the response modification factor (R) from 4.69 to 5.03, while the Cd value of the non-braced portal was 3.29 using braces was 3.02 and the Ω0 value of the non-braced portal was 3.50 and after using braces was 2.84. These findings open up opportunities for the application of better structural strengthening techniques in order to improve the safety and stability of buildings in earthquake-prone areas.

Introduction

In the construction field, maintaining structural stability is crucial, especially for buildings that have a high risk of lateral forces caused by earthquakes, such as those of concrete portal structures. Concrete portals with a two-dimensional (2D) design can serve as simulation models, which are commonly used in various applications such as bridges and high-rise buildings (Zarkasi et al., 2022; Wu et al., 2025; Yue et al., 2024; Kang et al., 2024). These constructions need to be designed to withstand lateral forces caused by wind, earthquake or other loads. In this study, the use of *Independent Wire Fibre Core* (IWFC) steel wire rope braces is an option to improve the structural stability. Thus, the researchers wanted to explore the effectiveness of IWFC utilisation in strengthening 2D concrete portals against lateral forces that could affect the safety of the building.

IWFC steel wire rope braces have unique characteristics that make them an attractive option in structural reinforcement. IWFC consists of *independent* steel wire fibres, which allow for more even load distribution and *flexibility* and are favourably compared with typical bracing systems (Steel, Concrete and Timber). According to research by (Zhang et al., (2020) in Zarkasi et al. (2017)), the use of IWFC can enhance the structure's resistance to lateral deformation by up to 30% compared to structures that do not use other braces. This shows the great potential of IWFCs in strengthening 2D concrete portals that are often vulnerable to lateral forces.

The stability of two-dimensional (2D) concrete portals is influenced not only by the type of material used, but also by the design and construction methods applied. Previous research by Atlaoui (2024) in Zarkasi et al. (2017)) showed that the use of appropriate bracing can reduce the risk of collapse in concrete structures exposed to lateral forces. Thus, it is important to understand the interaction between IWFC braces and concrete portals in the context of lateral forces. So, to achieve the objective of this study, the researchers will conduct a series of experimental trials to measure the performance of 2D concrete portals reinforced with IWFC braces. The results of this study are expected to provide a new perspective on structural strengthening techniques that can be applied in construction practice. In addition, this study also aims to provide information on the response modification factor (R), deflection amplification (Cd), and system over-strength (Ω0) related to the relationship between lateral load (v) and deviation (δ) used in building structure planning.

Literature Review

Concrete

Concrete can be defined as a combination of Portland cement or other hydraulic cement, fine aggregate, coarse aggregate, and water, which may or may not contain admixtures (SNI 1726:2019, 2019). Concrete has high compressive strength which is one of the main performances of concrete (Hamdani et al., 2024; Iffat, 2015; Behnood et al., 2017; He et al., 2010). Tests of the mechanical properties of concrete that are often carried out are compressive Strength (f'c) and modulus of elasticity (Ec), and poisson's ratio (v).

Compressive strength can be used to determine the quality of the concrete material, where the higher the desired strength of the concrete material is, the better the quality of the concrete produced (Mulyono, 2004; Ikpa, 2024; Tran et al., 2022; Hamada et al., 2022; Gupta & Sihag, 2022; Paudel et al., 2023). The compressive strength of a test specimen is determined based on the maximum stress level achieved at 28 days of age as a result of the compressive load applied during the test (Dipohusodo, 1993; Hughes & Watson, 1978; Pourbaba et al., 2018; Ispir et al., 2022; Zhang et al., 2024). To determine the compressive strength of concrete (f'c), calculations can be made using the formula listed below:

$$f_c' = \frac{P}{A}$$

Where f'c denotes the Compressive Strength of concrete measured in one MPa, P refers to the maximum applied load in Newtons (N), and A is the compressive area expressed in square millimetres (mm²).

The elastic properties of a material are expressed by the modulus of elasticity, symbolized by Ec. The modulus of elasticity is the ratio between the applied pressure and the change in shape per unit length in response to that pressure. In testing, the modulus of elasticity is usually measured when the compressive strength (f'c) ranges from 25% to 50%, which can then be calculated using a specific formula as follows (Badan Standarisasi Nasional, 2019b).

$Ec = \frac{S_2 - S_1}{\varepsilon_2 - \varepsilon_1}$ or $Ec = W_c^{1,5} 0{,}043 \sqrt{f'c}$

or for normal concrete is allowed to use the following equation:

$$Ec = 4700 \sqrt{f'c}$$

Where Ec is the modulus of elasticity of concrete measured in MPa, S1 refers to the stress under strain (ε1 = 0.00005), and S2 is the stress under strain (ε2), which is equivalent to 40%

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of the concrete compressive Strength (f'c). ε1 indicates the strain value at S1 which is 0.00005, while ε2 is the strain value at the S2 level. f'c is the compressive Strength of concrete measured in MPa, and Wc is the weight of concrete per unit volume expressed in kg/m³.

Poisson's ratio is the elasticity constant of a material, denoted by the Greek letter ν (nu). This ratio indicates the ratio between the change in strain in the axial direction and the change in strain in the transverse direction. When a unidirectional force is applied to concrete, producing strain and causing deformation in the material, the Poisson's ratio of that material can be calculated using the following formula:

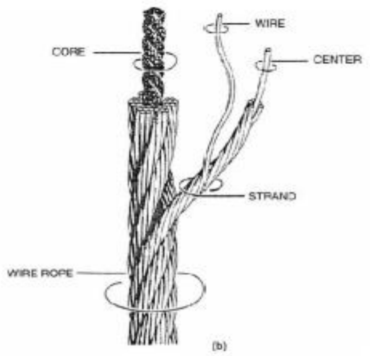
$$\upsilon = -\frac{d_{transfersal}}{d_{axial}} = -\frac{d_{\varepsilon y}}{d_{\varepsilon x}} = \frac{d_{\varepsilon z}}{d_{\varepsilon x}}$$

In this context, υ refers to the Poisson's ratio, $d_{Transverse}$ denotes the transverse strain (expressed as positive for tensile $_{axial}$ force and negative for compressive axial force), while d($_{axial}$) denotes the axial strain (positive for tensile axial force and negative for compressive axial force).

Steel Wire Rope (Wire Rope)

SNI 03-0076 (2008) explains that steel wire rope consists of a series of six or more strands of steel wire, which can be either zinc coated or not. The typical geometry of a steel wire rope can be seen in the following figure 1.

a. Independent wire rope core (IWRC)



b. Wire rope dengan inti serat

Figure 1.Typical Wire Roope Geometry

Wire Rope Safety Factor

To understand the SWL (Safe Working Load), which in Bahasa Indonesia is known as BKA (Safe Working Load), when using wire rope in accordance with its function, it is important to always consider the safety factors involved.

$$\text{SWL} = \frac{\text{Kekuatan Tali Putus } (Breaking\ Strength)}{\text{Faktor keamanan } (Safety\ Factor)}$$

The safety factors for different types of ropes are as follows: Idle ropes have a safety factor of 3.0 (pendant ropes), Walking ropes have a factor of 3.5 (hoist ropes), Sling ropes have a factor of 5.0 (weight lifting ropes), and Ropes for personnel reach 10.0 (man cage/man basket). The function of this safety factor is to anticipate rope breaking Strength, improper use, incorrect weight estimates, and other factors. To determine the safe Strength of steel wire rope, known as Safe Working Load (SWL), you can use certain formulas for a rough calculation that is safe enough.

$$SWL\ (Ton) = 8\ x\ D^2$$

With SWL; Wire rope safe working load (Tonnes), D; *Wire rope* diameter (mm)

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Structure Ductility

Declitality is the capacity of a structural element to deform when approaching the maximum load, without experiencing sudden collapse (Park and Paulay, 1975 in Pathurahman & Utami (2006). In reinforced concrete the term ductility is the ability of concrete to carry or withstand a large enough load and can deform *inelastically* before collapse. *Inelastic* graph can be seen in the following.

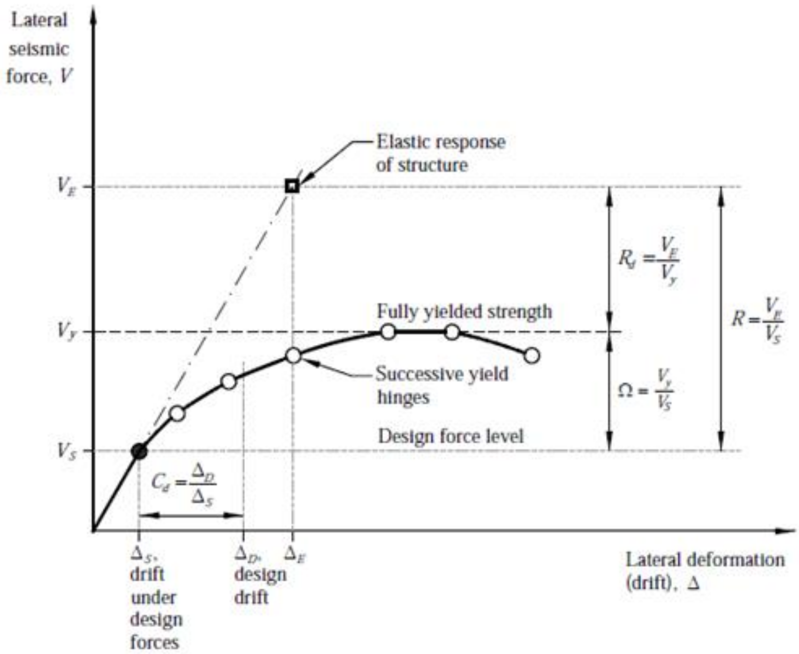

Figure 2. Inelastic Force to Deformation Curve

Source: FEMA P-750, (2009)

The figure above emphasises the importance of design parameters such as response modification coefficient (R), deflection amplification factor (Cd), and overstrength factor (Ω0). The response modification coefficient (R) describes the strength ratio of movement in a given soil, and the ratio R is expressed by the following equation:

$$R = R_D \, \Omega \text{ Or } R = \frac{V_E}{V_s}$$

Where *R*: *Response modification coefficient*, *Ω*: *Overstrength factor, R_d*: *Required ductility*$R_d = \frac{V_E}{V_y}$. Where R should be greater than or equal to 1.00. Thus, all structures are designed to withstand lower forces than the planned ground motions, resulting in structures that have an elastic linear response. Meanwhile, the deflection amplification factor (Cd) and overstrength factor (Ω0) can be expressed by the following equations:

$$C_d = \frac{\Delta_D}{\Delta_S} \text{ and } \Omega_0 = \frac{V_y}{V_S}$$

Where V_S: *Lateral seismic force* at *design force level*, V_Y: *Lateral seismic force* at *fully yielded strength* condition*,* V_E: *Lateral seismic force* at *successive yield hinges* condition. Δ_S: *Lateral deformation*, *drift under design,*Δ_D: *Lateral deformation, design drift* according to SNI 1726 2019,Δ_E: *Lateral deformation* under *successive yield hinges* condition,Δ_y: *Lateral deformation in fully yielded strength* condition.

Deviation or Deformation

Deformation, also known as deviation, is a change in the shape, size, or position of an object due to the application of force or a change in temperature. If an object is deformed and can

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return to its initial state after the applied force is removed, this is referred to as elastic deformation. On the other hand, there are deformations that cannot return to their original shape even after the force has been removed, which is called plastic deformation. In SNI 1726:2019, deformations are regulated according to certain categories to ensure safety and comfort for occupants. More information about this can be seen in the table provided.

Table 1. Permit Deviation of Each Floor, Δaab

Structure	Category Risk		
	I atau II	III	IV
Structures, other than masonry shear wall structures, four storeys or less with interior walls, partitions, ceilings and exterior wall systems that have been designed to accommodate inter-storey level deviations	0,025 h_{sx}	0,020 h_{sx}	0,015 h_{sx}
Brick cantilever shear wall structure	0,010 h_{sx}	0,010 h_{sx}	0,010 h_{sx}
Other brick shear wall structure	0,007 h_{sx}	0,007 h_{sx}	0,007 h_{sx}
All other structures	0,020 h_{sx}	0,015 h_{sx}	0,010 h_{sx}

Source: SNI 03-1726-2019

[a] *$h_{(sx)}$ is the height of the level below level x*

Performance Base Design

Performance-Based Design is a building design method that uses the behaviour of a building when exposed to a certain level of earthquake as a reference. Meanwhile, Performance Level refers to a limit on the level of damage or condition of a building as indicated by the level of physical damage that occurs. According to (FEMA P-750, 2009), building performance levels are divided into several categories, namely:

Operational or Serviceable

At this level, the building can still function fully despite the earthquake. This is because the main structural elements were not damaged, while the non-structural elements suffered very minimal damage and did not cause any problems.

Immediate Occupancy

In this state, the building can still operate even though there is little damage to the structural parts and a slight decrease in function in some non-critical service units. The damage is minor, and the repairs do not interfere with building users. Therefore, buildings at this level can be used immediately after an earthquake.

Live Safety

At this level, the safety of building users is maintained, even though the building cannot function fully and has moderate to high levels of damage.

Collapse Prevention

In this situation, the safety of building users is threatened, and the building is potentially dangerous to use because it is about to collapse. Although the building is still standing, the extent of the damage is severe, although structural collapse can still be avoided.

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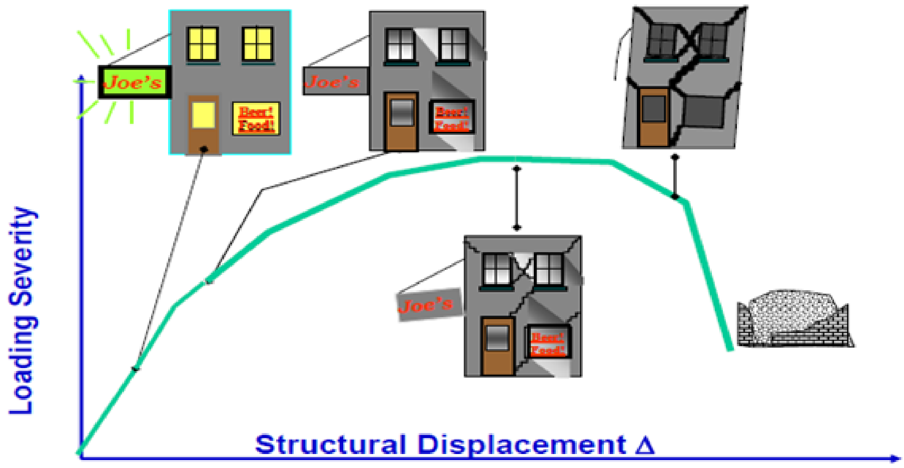

Figure 3. Global Response and Performance Level

Source: (FEMA P-451, 2006)

Methods

Mix Design

The concrete mix design used is SNI 03-2824-2000 which for structural concrete should not be below 20 MPa. The design of the mixture composition for 1 m3 of concrete is presented in the following table:

Table 2. Concrete mix design

No.	Concrete Quality (f'c) MPa	Portland Cement (kg/m³)	Sand (kg/m³)	Gravel (kg/m³)	Suling Water (Litre/kg)	FAS
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	20	342	747	1121	205	0,59

Test Item Design

In order for this study to achieve the desired objectives, the researchers designed a concrete portal with dimensions of 1.00 m (Width) and 1.50 m (Height) by varying the type of *bracing* used to resist lateral loads.

Table 3. Samples and Variations of Test Objects

No.	Description	Code	Total	Test Type	Description
I	Uji Portal Beton				
a.	Empty portal	PK	1	Loading Frame, Data Loager dan LVDT	Reviewed until Structure fails
b.	Empty portal with wire rope bracing	PDBW	1	Loading Frame, Data Loager dan LVDT	Reviewed until Structure fails
	Total Test Items		**17**		

The portal tests were conducted by applying a one-way load to mimic the lateral forces generated by an earthquake (static lateral). Thus, the simulation of this test can be seen in the following figure:

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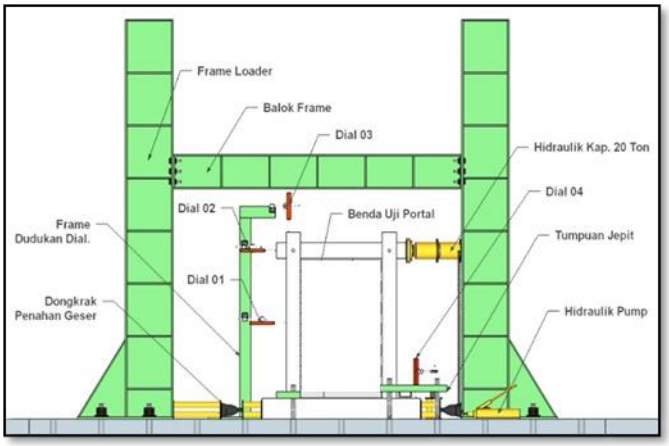

Figure 4. Simulation of Testing on Loading Frame

Figure 5. Placement of Test Objects Before Testing on Loading Frame

Research Flowchart

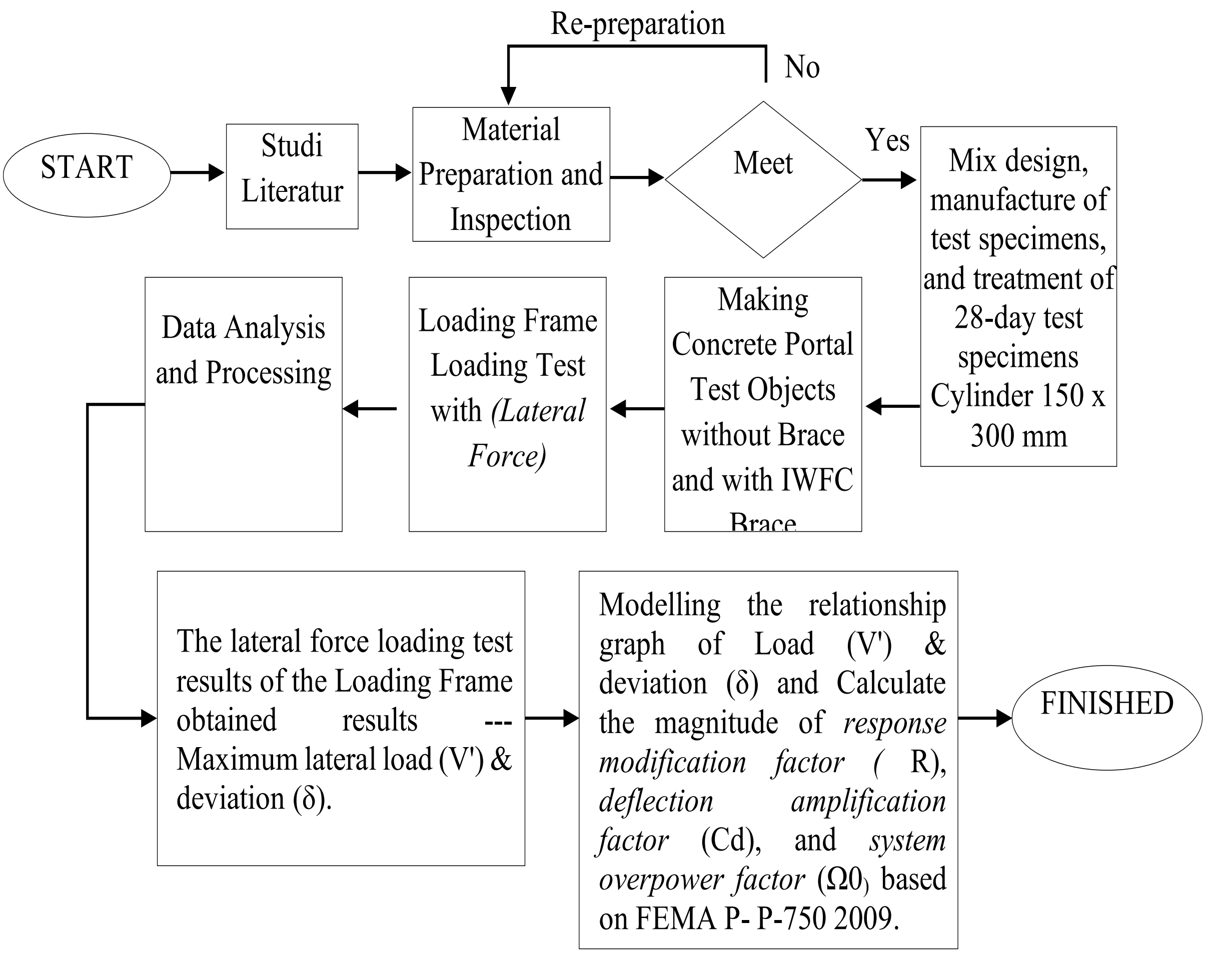

Figure 6. Research Flowchart

Results and Discussion

Laboratory Test of Concrete Portal

Laboratory testing of the concrete portal was the main objective of this study. The concrete portal test results can be seen in the following Table:

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Table 4. Concrete Portal Testing.

Test Item Code	Load Max. (v) kN	Deviation Max. (δ) (mm)	Base Length *Bracing* (mm)	Length Change *Bracing* (mm)	Strain During *Bracing* Fail (ε')
a	b	c(1)	d	e	f
Unbraced Concrete Portal	14,00	57,90			-
Concrete Portal with Braces	26,13	69,04	1802,80	1852,2	0,0274

Testing of Concrete Portals without Braces

The laboratory test results can be seen through the relationship between capacity and deviation (V - δ) shown in the following figure.

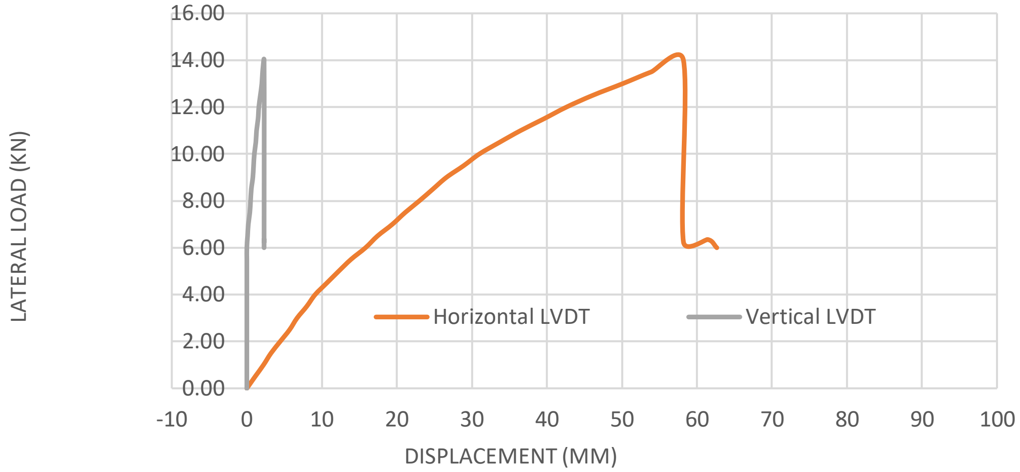

Figure 7. Graph of (V) and (δ) Testing Portal without Brace

The graph above shows the maximum load of *(V)* = 14.00 kN with a deviation of *(δ)* = 58.20 mm. As the load increases, in addition to the horizontal deviation, there is also a vertical deviation of 2.30 mm. Due to the large load on the test specimen, the *portal* without braces is *uplifted* by 0.30 mm, so the horizontal and vertical deviation values are corrected to 57.90 mm and 2.30 mm, respectively.

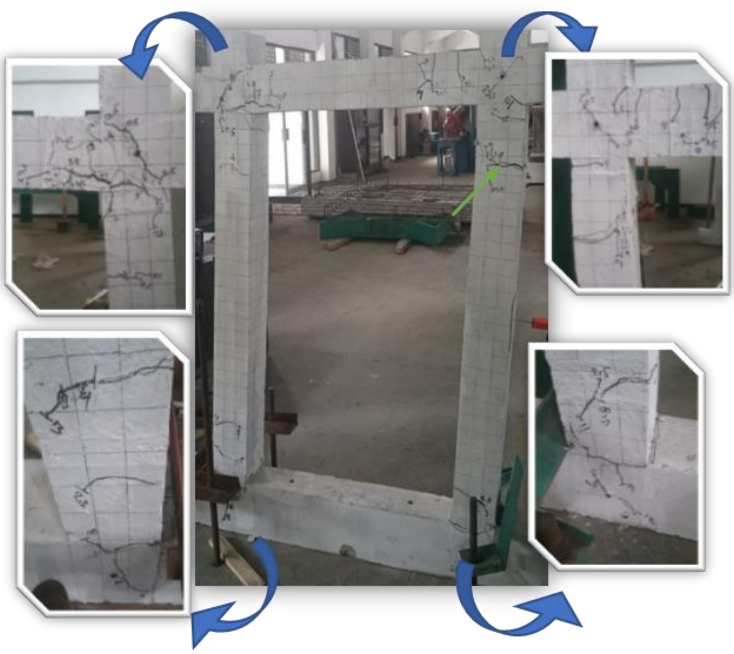

Figure 7. Testing Documentation of Portal without Brace

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Testing Concrete Portals with Braces

The test results are illustrated through the following relationship between capacity and deviation (V - δ).

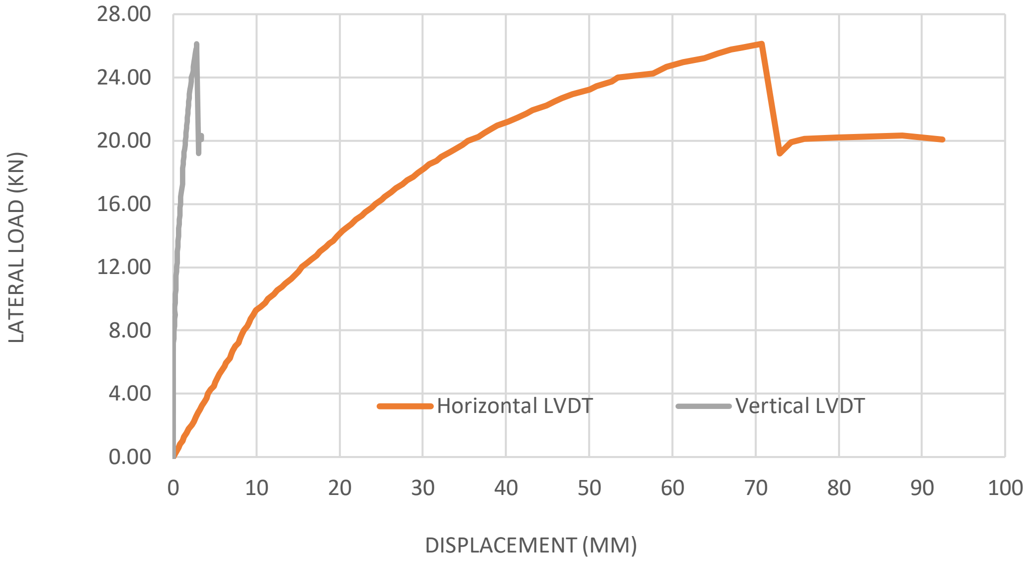

Figure 8. relationship between capacity and deviation

The graph above shows the maximum load of *(V)* = 26.13 kN with a deviation of *(δ)* = 70.74 mm. As the load increases, in addition to the horizontal deviation, there is also a vertical deviation of 3.38 mm. Due to the large load on the test specimen, the *portal* without braces has an *uplift of* 1.70 mm, so the horizontal and vertical deviation values are corrected to 69.04 mm and 1.68 mm, respectively.

Figure 9. Documentation of Portal Testing with Braces

Comparison of Testing of Concrete Portals without Braces with Braces

Comparison of portal capacity is a comparison of the ability of the portal to accept lateral loads both monotonically and laterally. The test results show an increase in capacity (v) by 16.13%. The use of braces can provide user comfort by being able to reduce deviation *(δ)* by 30.43%.

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Specifies R, Cd) and Ω

The factors R, Cd, and Ω were determined based on a graph depicting the relationship between load capacity and displacement or deviation. The results of these calculations can be seen in the table below:

Table 5. From the graph of V and δ

Test Item Code	Drift Under Design Forces	Design Drift	Elastic Response Drift	Design Forces Level	Fully Yielded Strength	Elastic Response Of Structure
	(Δ_s)	*(Δ_D)*	*(Δ_E)*	*(V_s)*	*(V_y)*	*(V_E)*
1	2	3[(a)]	4	5	6	7
Unbraced Concrete Portal	9,11	30,00	42,70	4,00	14,00	18,75
Concrete Portal with Braces	9,94	30,00	50,00	9,20	26,13	46,28

The design drift is set at 2% of the building height (0.02hx) in accordance with the drift provisions listed in SNI 1726:2012 for other types of building structures. This aims to make occupant comfort a top priority in the design of building structures, as well as to prevent too large a value of ρ delta.

Table 6. R, Cd and Ω factors.

Test Item Code	Required Ductility	Overstrength Factor	Response Modification Coefficient	Deflection Amplification Factor
	(Rd)	*(Ω)*	*(R)*	*(Cd)*
8	9 = 7/6	10 = 6/5	11 = 7/5	12 = 3/2
Unbraced Concrete Portal	1,34	3,50	4,69	3,29
Concrete Portal with Braces	1,78	2,84	5,03	3,02

The R, Cd and Ω factor tables show the improvement in the response of a structure to the applied load. The greater the *response modification coefficient (R)* obtained from a structural system, the better a structure reduces the lateral loads that occur due to earthquakes (National Standardisation Agency, 2019).

Enhancing Seismic 2D Concrete Portals Performance Using IWFC Steel Wire Rope Braces

Experimental outcomes of the present research indicate massive enhancements in the structural performance of two-dimensional (2D) concrete portals strengthened with Independent Wire Fibre Core (IWFC) steel wire rope braces. With the addition of IWFC braces, lateral load resistance increased by 16.13 percent, (14.00 kN without braces to 26.13 kN with reinforcement). This observation confirms the efficacy of bracing system to provide lateral strength that is paramount to seismic resistance. This kind of enhancement corresponds to the previous research studies, which underline the effectiveness of tensile-based bracing systems in redistributing lateral loads and countering localized structural collapses (Paulay & Priestley, 1992). Similar results are shown by Zhang et al. (2020), who proved that the lateral capacity of steel-concrete hybrid buildings could be extended more than 30 percent using wire rope bracing systems, once again supporting the structural usefulness of high-tensile flexible elements in seismic environments.

Besides load resistance, the research also realized a significant 30.43 percent decrease in structural deformation where the deviation values reduced to 1.68 mm, as against the 2.30 mm earlier. This is of interest especially to structural performance in earthquakes where drift

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control is critical to ensuring safety and functionality. As noted by FEMA P-750 (2009), lateral displacement ductility can be too large, which may cause non-structural damage, usability loss of buildings, and eventually structural collapse. IWFC braces help to reduce deformation under load, thereby helping to limit inter-story drift, which is a key design code requirement in, among others, SNI 03-1726-2019 and Eurocode 8 (CEN, 2004). The capability of the braced portal to stay within these limits indicates that the systems may contribute buildings to achieve Immediate Occupancy or even Operational level of performance outlined in performance-based seismic design codes (FEMA P-58, 2012), meaning that buildings will still be usable even after moderate earthquakes.

Moreover, increased seismic response indicators, that is, the response modification coefficient (R), deflection amplification factor (Cd), and overstrength factor (Omega 0) reflect greater structural advantages of IWFC incorporation. The R value improved form 4.69 to 5.03 which indicates that the ductility is enhanced and the ability of braced system to dissipate energy through controlled inelastic deformation is also improved. In seismic design, one would want to have a higher R value so that a structure can be built with reduced seismic force and still be safe (Park & Paulay, 1975; Krawinkler & Miranda, 2004). The minor decrease in Cd of 3.29 to 3.02 in the braced model also shows better control over lateral deflection resulting in safer and more economical design. In the meantime, the decreased value of $\Omega 0$, as 3.50 to 2.84, indicates that the strength of structural system is being mobilized more effectively and there is less needless overdesign, meaning that resources may be more effectively distributed, which is a pragmatic benefit stressed within the displacement-based seismic design ideology.

Such increment in performance can be ascribed to material behavior and mechanical properties of IWFC braces. IWFC ropes are made of many independent steel wires, which makes them exhibit a distributed strain behavior and become more flexible, both favorable properties in dynamic loading conditions. According to Huang et al. (2025), the elongation and energy dissipation capacity of such multi-core tensile systems is higher than that of monolithic steel braces. Their capacity to creep under rising loads helps to dissipate the risk of unexpected collapse, and makes the structure more flexible in its response to seismic actions. Also, Khosravi (2021) noted that this type of bracing systems induces stable hysteretic behavior and post-yield performance, which is vital in structures that are likely to undergo several seismic cycles.

Practically, as an engineer, IWFC braces are advantageous in a number of ways. They are light weight and modular in nature and thus find application in retrofitting of existing structures, particularly those that were erected before the establishment of the modern seismic code requirements. The braces might be an economical alternative to enhance the seismic performance in post-disaster scenarios or in developing nations with Restricted structural budgets, where extensive reconstruction is undesirable (Ali, 2007). Their flexibility also enables them to be installed in a customized manner in restricted or irregular buildings, something that is not possible in most cases when using the rigid bracing systems.

Although the study presents strong evidence on the structural advantage of the IWFC braces, it also enlightens the necessity of the additional research. The loading procedure of the experimental was monotonic, static, whereas the actual earthquakes cause cyclic, reversing forces. This way, further research must consider reversed cyclic loading to determine fatigue behavior, strain accumulation, and long-term degradation parameters that are important in assessing performance through the lifecycle of a structure (FEMA P-695, 2009; Xu et al., 2023; Nijssen, 2006; Bogdanov et al., 2023; Passipoularidis et al., 2011). Also, an investigation of the effects of changes in wire diameter, anchorage methods, and brace framing could yield to optimum designs dependent on the type of buildings or level of seismic hazard.

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Conclusion

Laboratory test analysis results obtained an increase in load resistance capacity (v) of 16.13%. The value of the increase in capacity from 14.00 kN to 26.13 kN before and after the installation of the brace. In addition to increasing the load resistance capacity of the brace is also able to reduce the occurrence of displacement or deviation by 30.43% from 2.30 mm to 1.68 mm. From the graph of the relationship between v and δ of the portal test in the laboratory, the value of the response modification factor (R), the deflection amplification factor (Cd), and the system strength factor (Ω0) before and after the installation of the brace is obtained, namely the value of R for the non-braced portal of 4.69 and using the brace of 5.03, while the value of Cd for the non-braced portal is 3.29 and using the brace of 3.02 and the value of Ω0 for the non-braced portal is 3.50 and after using the brace it becomes 2.84.

From this experimantal study, to make it more perfect in the future, it is necessary to add or change the lateral load to a cyclic or alternating load to make it more realistic to the earthquake. In addition, the use of bracing in future research can be further varied into several types.

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